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Historical Perspective on Habitat Essential to Bristol Bay Red King Crab

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Abstract

The Alaska red king crab, *Paralithodes camtschaticus*, has one of the most information-rich assessment and exploitation histories of any species in the eastern Bering Sea. Yet unsound assumptions and misconceptions persist as to the species' basic biology, ecology, and habitat requirements. These include (1) temperature is the dominant factor governing the distribution and abundance of red king crab, making them so unpredictable in their movements that no particular habitat can be designated as more essential than another within their 150,000 km^2 Bering Sea range; (2) early no-trawl refuges (e.g., the Japanese Broodstock Sanctuary and the Pot Sanctuary) were implemented to resolve fishing-gear conflicts rather than to protect red king crab from trawling; (3) protection from bottom trawling is more important for juvenile red king crab than for the multiparous broodstock with its relatively high reproductive value; (4) all male red king crab with a carapace length of 120 mm or greater, regardless of their molt status, are capable of mating with one or more females each year; and (5) the Bristol Bay red king crab stock is assumed to be regulated largely by compensatory mechanisms that cause reproductive success to be highest when spawning-stock abundance is lowest, thus ensuring that the stock will recover from overfished abundance levels once fishing is halted. This paper uses information from surveys conducted as early as 1941 to examine these assumptions and to provide the detail and

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historical perspective needed to identify habitat essential to an intact population of Bristol Bay red king crab.

Introduction

The Bristol Bay red king crab stock has a long history of exploitation. According to Blackford (1979), the Japanese began fishing for king crab in the Bering Sea in the 1920s and, during the 1930s, were taking more than 13,000 t (metric tons) of whole crab per year from Bristol Bay north of the Alaska Peninsula. King crab fishermen from the Soviet Union entered the eastern Bering Sea in 1928, and by 1930 they were taking some 4,000 t annually (Blackford 1979). U.S. fishermen, encouraged by the findings of an exploratory survey conducted by the U.S. government (USFWS 1942), entered the Bristol Bay red king crab fishery in 1946. Although the Bering Sea produced most of the red king crab caught by American fishermen during the 1940s and early 1950s, the U.S. catch was small compared to that of Japan and Russia. By the mid 1950s, newly opened fishing grounds in the greater Gulf of Alaska (GOA) were out-producing the Bering Sea, and in 1966 the U.S. catch of 70,000 t (Orensanz et al. 1998) in the GOA dwarfed the U.S. Bering Sea catch of 450 t and was substantially larger than the Bering Sea catch of 19,000 t for Japan and the USSR combined (Otto 1981). However, in the early 1960s, it became clear that overfishing had begun to deplete Alaska's king crab resources. The Japanese reported in 1963 that their catch per unit of fishing effort in the Bering Sea had fallen by two-thirds since 1960. Also, the U.S. Alaska catch, 90% of which came from the GOA, peaked in 1966 and declined by 65-70% over the next three years (Blackford 1979).

By 1970, multiple conservation measures had been implemented, several of which were intended to reduce the direct effects of trawling on king crab. In 1959, Japan set aside a 67,000 km^2 area of Bristol Bay, where trawling by the Japanese fishing fleet was banned. In 1961, trawling as a crab fishing method was outlawed in all of Alaska's waters. In 1964, an international agreement was forged among the United States, Japan, and the USSR, whereby trawling was prohibited in a 20,000 km^2 tract of prime red king crab habitat in Bristol Bay waters, off the western end of the Alaska Peninsula. Also, during the 1960s, diplomatic pressure and evolving international conventions squeezed the Japanese and USSR king crab quotas until the harvest of Bering Sea king crab became essentially an American enterprise. As the GOA king crab stocks began to dwindle after 1966, U.S. fishermen turned to the Bering Sea, where the U.S. share of the king crab catch, less than 5% during 1958-1966, rose sharply to more than 50% by 1969 (Otto 1981). By 1970, the stage was set for an 11-year period (1970-1980) of escalating American exploitation unmatched in the history of Alaska fisheries—a period in which the Bering Sea king crab harvest increased exponentially, doubling every three years, until a cumulative, 11-year total of nearly 300,000 t and $3 billion worth of crab (in 2007 dollars) was extracted. Because managers have redefined the Bristol Bay red king crab population to be a population with no history prior to 1983, this highly exploitive 1970-1980 period, which provided considerable largesse to the state of Alaska and brought the Bristol Bay stock to the brink of commercial extinction, is presently excluded from the 1983-1997 baseline average used to evaluate whether the stock is overfished (Dew and McConnaughey 2005, p. 936).

The abrupt 1981 collapse of the Bristol Bay stock, the second largest king crab population in the world (Rodin 1990) and a stock that had been profitably exploited by three nations for half a century, was an unsettling event. However, the management community was confident that the size-sex-season management of Bering Sea king crab, whereby only large males (and no females) are harvested during a relatively short season, was sufficiently conservative that overfishing could not have been a significant factor in the collapse (Otto 1986, Wooster 1992). Therefore resource managers concluded that the 1977-1983 disappearance of more than 90% of the adult stock was a natural event unrelated to man's fishing and "largely beyond control" (Otto 1986, p. 105), despite record levels of fishing mortality (Dew and McConnaughey 2005). However, size-sex-season alone, without the support of reliable stock-size estimates (e.g., Dew 2008) and a well-developed understanding of the target species' behavior and ecology, cannot lead to fully informed management decisions.

There are several assumptions integral to the present management system that have persisted since the collapse and that create the potential for unexpected collapses in the future. Some of these assumptions are (1) within the geographic range of Bering Sea red king crab, no particular habitat is essential (NMFS 2005); (2) all male red king crab with a carapace length (CL) ≥120 mm are capable of mating with one or more females each year (Zheng et al. 1995); (3) the podding behavior of juvenile red king crab does not continue into adulthood (Powell and Nickerson 1965, Incze et al. 1986, Otto 1986, Armstrong et al. 1993, Witherell 1998, Ackley and Witherell 1999); and (4) the uncertainty associated with NMFS' red king crab population size estimates is sufficiently low (e.g., Otto 1986) that it can be ignored when setting harvest quotas. While all of these assumptions deserve attention, the primary purpose of this paper is to critically examine the assumption that, within the geographical range of Bristol Bay red king crab, no particular habitat is essential. This assumption is based on the rationale that changes in red king crab distribution and abundance are governed by unpredictable changes in water temperature and oceanographic regimes. Therefore the crab need all of the habitat available to them, and they are not dependent on any particular habitat within their general distribution (NMFS 2005).

Essential habitat

Since the inception of the Fishery Conservation and Management Act in 1976 (later amended, and known as the Magnuson-Stevens Act), habitat issues for species included within the fisheries of the United States have been of increasing concern. This concern culminated in 1996 with Congress enacting the Sustainable Fisheries Act (SFA), which expanded existing federal authority to identify and protect essential fish habitat (EFH). The SFA requires each regional fisheries management council, after receiving recommendations from the National Marine Fisheries Service (NMFS), to amend its fishery management plans (FMPs) to describe (in text) and identify (with maps) essential habitat for each species managed by the council. Perhaps understanding that animals are most abundant in their preferred habitat, NMFS (2005, Appendix E) recommended to the North Pacific Fishery Management Council (NPFMC) that relative abundance information, when available, should be used to designate EFH areas that are smaller than the general distribution for the species of interest. More narrow designations would help to prioritize management efforts and would be a more effective tool for habitat conservation. NMFS (2005, Appendix E) also reminded the NPFMC that defining EFH as a species' general distribution (the geographical range encompassing 95% of the population) is not consistent with the Magnuson-Stevens Act or the EFH regulations because the general distribution fails to distinguish EFH from total available habitat. Nevertheless, in the *Final Environmental Impact Statement for Essential Fish Habitat Identification and Conservation in Alaska*, hereafter referred to as the EFH EIS (NMFS 2005), EFH for red king crab and other FMP species in Alaska was defined as the general distribution. Among the reasons given for this approach to habitat evaluation was that the relative value of habitats inferred from a species' abundance within those habitats, as determined from stock-assessment surveys used to manage the species, is not based on the best available scientific information (DiCosimo 1999) because current survey information does not adequately address unpredictable annual differences in spatial distribution (NOAA 1999). According to the NPFMC, "The Council chose not to endorse Alternative 4 (Presumed Known Concentration), which NMFS had recommended (see Appendix E), because of concern that the narrower EFH designations resulting from Alternative 4 might not account for changes in habitat usage over time" (NMFS 2005, pp. 2-60).

Such concerns may be warranted for FMP species with relatively short, information-poor histories of assessment and exploitation. However, Alaska red king crab has one of the most information-rich assessment and exploitation histories of any species in the eastern Bering Sea (e.g., Zimmerman et al. 2009). Sometime in the late 1930s, Congress appropriated funds for a two-year (1940-41) survey of Alaska's fishery resources. The results of the eastern Bering Sea survey of 1941, which discovered very large concentrations of crab within 55 km from shore between Unimak Island and Port Moller, spurred the growth of the king crab industry in the early 1940s (Blackford 1979). Similarly, a second government survey in 1948 found its largest aggregations of crab located in nearshore waters between Amak Island and Port Moller. In 1949, relying on the federal government's exploratory work in 1941 and 1948, Deep Sea Trawlers, the first private-enterprise king crab venture in the United States and the precursor to Wakefield Seafoods, saved itself from probable bankruptcy by locating heavy concentrations of king crab off Amak Island, where government surveys predicted they would be. The company continued to trawl on the Amak crab for nine months, from April to December 1949, freeze-packing more red king crab weight (404,000 lbs, equivalent to about 800 t of whole crab) in 1949 than in 1947 and 1948 combined (Blackford 1979).

Thus, information from a decade of assessment surveys and commercial trawling operations in the southeastern Bering Sea during the 1940s suggests that, rather than being unpredictable, the preferred habitat of adult red king crab was well defined, extending from Unimak Island (Cape Serichef) to Port Moller, with its center near Amak Island. Further evidence for the persistence and stability of this habitat preference may be found in the fact that more than 20 years later this same area, north and west of Unimak Island and the western Alaska Peninsula to Nelson Lagoon near Point Moller, was set aside as a red king crab refuge where trawling and tangle-net fishing was prohibited and only pots could be used for crab fishing (Naab 1968a,b; 1971). Thus, America's first Bering Sea no-trawl zone, a 20,000 km^2 subset of the larger 67,000 km^2 Japanese no-trawl sanctuary, was established through negotiations with Japan and the Soviet Union to protect red king crab in habitat considered by the United States to be essential to the species in Alaska. To clarify, the American no-trawl zone, known as the Pot Sanctuary (Fig. 1, Table 1), is often confused in contemporary literature (e.g., Fredin 1987, Ackley and Witherell 1999, Dew and McConnaughey 2005) with the no-trawl sanctuary established by the Japanese to protect the red king crab broodstock (egg-bearing females) from Japan's trawl fleet. For lack of more accurate terminology, I will refer to the larger no-trawl zone as the "Japanese Broodstock Sanctuary" (Table 1).

History and purpose of no-trawl sanctuaries

It is important to understand that the primary objective of early no-trawl sanctuaries, namely the 1959 Japanese Broodstock Sanctuary and the 1964 Pot Sanctuary, was to protect Alaska's red king crab resource

Table 1. Additional information on the four red king crab no-trawl refuges of Fig. 1. The Japanese Broodstock Sanctuary and the Pot Sanctuary no longer exist, after being breached by trawling shortly after passage of the 1976 Fishery Conservation and Management Act. The southern 16-17% of the Red King Crab Savings Area is routinely subjected to trawling for flatfish in what is known as "bottom-of-the-box" trawling.

Refuge	Size (km^2)	Location	Protection	Years	Prohibited	Signatories
Japanese Broodstock Sanctuary	67,000	Coastal and offshore waters from 160°W to 165°W	Entire RKC broodstock	1959-1977	Japanese trawl fleet	Japan
Pot Sanctuary	20,000	Coastal waters from 162°W to 165°W	Highest-value RKC broodstock	1964-1977	All trawling, tangle nets	U.S., Japan, USSR
Red King Crab Savings Area	Nominal 14,000, actual 12,000	Offshore waters, 50-100 naut. mi. north of Amak I.	Adult (mostly male) RKC	1995 to present	Most trawling	U.S.
Bristol Bay Nearshore Trawl Closure	65,000	Bristol Bay east of 162°W	Juvenile RKC	1997 to present	All trawling	U.S.

from the effects of bottom trawling, considered to be so destructive of red king crab that, upon gaining statehood in 1959, Alaska quickly outlawed trawling as a king crab fishing method (Blackford 1979). However, according to contemporary accounts, the no-trawl sanctuaries of the late 1950s and early 1960s were established solely to resolve fishing gear conflicts (Fredin 1987, Ackley and Witherell 1999, NMFS 2005, Witherell and Woodby 2005). No mention is made in these accounts of the intended role of no-trawl sanctuaries in conserving Alaska's king crab resource (e.g., Naab 1968a). For example, Witherell and Woodby (2005, p. 3) state that the 1959 Japanese Broodstock Sanctuary was established "to limit interactions between its trawl fleet and its crab pot fleet." However, it is unlikely that the Japanese, considered to be the originators of the king crab industry in Alaska, and who had used tangle nets (Miller 1965), not pots, to pursue their Bristol Bay crab fish-

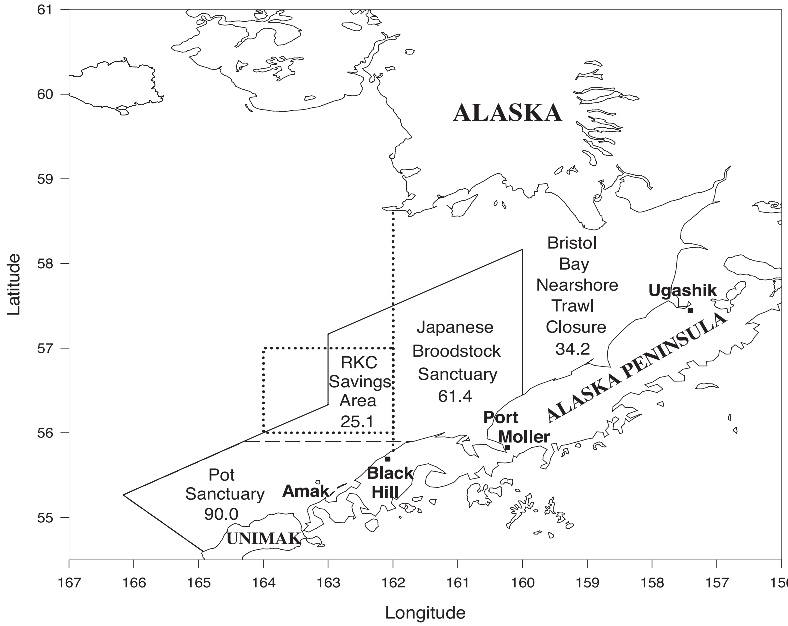

Figure 1. Refuges designed to protect the Bristol Bay red king crab population from the effects of trawling. Historic refuges (the 1959 Japanese Broodstock Sanctuary and the 1964 Pot Sanctuary) protected 89% of the baseline (1958) broodstock, while today's refuges (dotted lines) protect 48% (see Table 1 for additional information). The numbers in each refuge represent the baseline multiparous broodstock densities (number per hour of trawling in 1958).

ery since the 1920s (Blackford 1979), waited until 1959 to address gear conflicts. Moreover, the boundaries of the Japanese no-trawl sanctuary closely conformed to the Bristol Bay distribution of mature female king crab (Dew and McConnaughey 2005) but excluded the male molting grounds 150-200 km north of Unimak Island, which were the focal point of Japan's autumn tangle-net fishery (Takeshita et al. 1990). Because gear conflicts that might have existed among various Japanese fishing fleets would not have been resolved by the 1959 Japanese no-trawl zone (the autumn tangle-net fishery was outside the zone), it is more logical that the intent of the 67,000 km^2 sanctuary was to protect the broodstock from trawling. As precedent, the Japanese (Marukawa 1933) designed a similar reproductive refuge for Kamchatka red king crab, as pointed out by Dew and McConnaughey (2005).

The Pot Sanctuary

Unlike the Japanese Broodstock Sanctuary of 1959, intense international gear conflicts did play a prominent role in the formation of the 1964 Pot Sanctuary. After World War II, the Japanese resumed fishing in the Bering Sea in 1953, and USSR fleets re-entered the Bering Sea in 1959, touching off a fierce rivalry for Bristol Bay red king crab. The rapid escalation in competition resulted in increased fishing pressure, which alarmed Americans concerned about the future of Bering Sea red king crab (Blackford 1979). Gear conflicts arose because the Americans used mobile gear (bottom trawls) and the Japanese and Soviets used fixed gear (tangle nets) to fish for crab. American trawlers during the late 1940s discovered that king crab aggregations could be found at certain spots at particular times. After 1950, using new technology to take advantage of the crabs' predictable behavior, American trawlers devised "radar fishing" to help them stay on the foraging crab aggregations and, "with the assistance of naval polar plotting sheets, could systematically work over an area and clean out an entire school of crabs" (Blackford 1979, pp. 22-23). Problems arose as the Japanese (and the Soviets) adapted to the American strategy by surrounding the trawlers' radar-reflecting buoys with miles of tangle nets, thus obstructing further trawling. These conflicts occurred most frequently in waters within a 100 km radius of Amak Island, which in the early decades of America's king crab industry was the most productive king crab habitat in the Bering Sea.

By 1960, the king crab fishery off Unimak and the western end of the Alaska Peninsula was chaotic, with three nations (United States, Japan, and Soviet Union) fishing for the same resource at the same time, using three different types of fishing gear (pots, trawls, and tangle nets). The bottom trawl, which by 1953 was the main gear type used by Americans to take king crab (Miller 1965), was generally recognized as an inefficient, wasteful, and destructive way to fish. In 1961 the Alaska Department of Fish and Game banned trawling in all of the state's waters (within three miles of land) (Blackford 1979). Seven years previously, in 1954, the use of tangle nets in Alaska waters was also outlawed, although the federal government's 1941 survey demonstrated that tangle nets, because they were selective for the relatively mobile, hard-shell males sought by the fishery (USFWS 1942), caused substantially less collateral damage than trawls. Also, it was becoming evident that, for Americans (who disliked picking through tangle nets), pot fishing was the most efficient method of harvesting king crab in terms of productivity per man-hour worked (Miller 1965). Therefore, to impose some order on the fishery and to eliminate trawling on the richest king crab resource remaining in the Bering Sea and the Gulf of Alaska, the Pot Sanctuary at the western end of the Alaska Peninsula was established in 1964. Because of its importance as America's first trawl-free refuge established specifically for red king crab (e.g., Naab 1968a), and because of the confusion and inadvertent revisionism in the literature surrounding this conservation effort, the boundaries of the 1964 Pot Sanctuary are presented here (after Beale 1971): Cape Serichef (54.6ºN, 164.93ºW) northwest 108 km to 55.2667ºN, 166.1667ºW, then northeast 138 km to 55.9ºN, 164.2833ºW, then east 161 km to a point (55.9ºN, 161.7ºW) on the Alaska Peninsula between Black Hill and Nelson Lagoon (near Port Moller). That priorities have changed since the 1960s is evident from the fact that the former Pot Sanctuary, better known today as Cod Alley, is now the most heavily trawled area in the eastern Bering Sea (Dew and McConnaughey 2005); and the EFH EIS (NMFS 2005, p. L-17) tells readers that, as habitat for Alaska red king crab, the area north of Unimak ". . . was not particularly important prior to [the mid to late 1970s] and has not been important since."

Protection from trawling, then and now

"The diminution of future population increase produced by removing a single animal of a given age from a population may be termed the reproductive value of that individual." (Slobodkin 1961, p. 50). The reproductive value of an egg-bearing female is thus greater than that of a juvenile, whose probability of dying from natural mortality before contributing to the next generation is relatively high. Collectively, egg-bearing females form the broodstock, which is that part of the population with the greatest reproductive value, and it is the broodstock that should receive the highest priority in management plans to protect the reproductive potential of the stock from the effects of trawling. The Bristol Bay red king crab broodstock is most vulnerable to trawling after females have returned from spawning in relatively trawl-free nearshore waters to incubate their eggs in deeper waters during the next 11 months. But because the standard NMFS Bristol Bay survey is conducted during late May–early June while red king crab are spawning inshore, much of the broodstock is unavailable to the survey, and the distribution of post-spawning females remains largely unknown at the completion of the standard survey (Dew 2008). Of all the red king crab surveys since 1941 (when 64% of the crab were caught on spawning grounds well inshore of the NMFS survey boundary), only the two-stage survey of 1958 provided information sufficient to define the broodstock distribution in its relatively vulnerable egg-incubation phase (Dew 2008).

Using 1958 as the baseline with which to define a Bristol Bay broodstock configuration capable of sustaining an intact population suggests that today's refuge arrangement is inadequate to support a broodstock with a reproductive capacity sufficient to rebuild the stock. The historic no-trawl refuge consisted of the Japanese Broodstock Sanctuary and included the 20,000 km^2 Pot Sanctuary (Fig. 1, Table 1). This 67,000

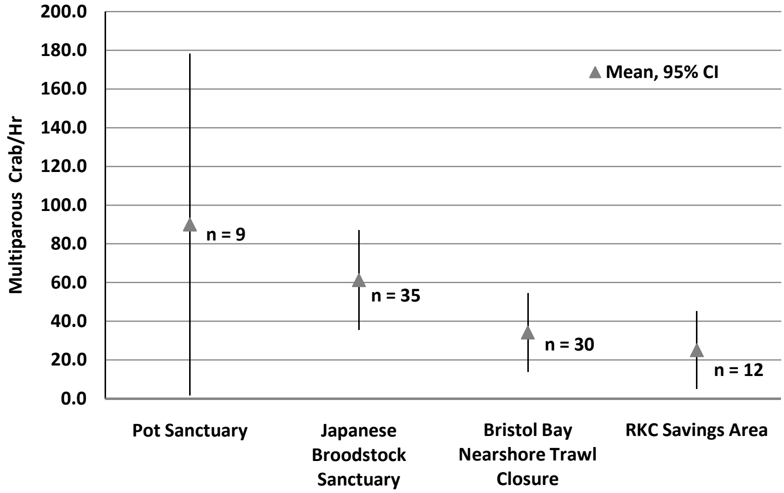

Figure 2. The June-July 1958 abundance trend of the Bristol Bay red king crab multiparous broodstock (females ≥100 mm CL), used here to rank the relative effectiveness of four no-trawl refuges (NMFS unpubl. data). Broodstock abundance was highest in the Pot Sanctuary (now Cod Alley) and lowest in today's refuges. n = number of tows.

km^2 area, implemented in 1959, provided a no-trawl refuge for some 89% of the baseline broodstock. By comparison, today's Bristol Bay Nearshore Trawl Closure (65,000 km^2) and the Red King Crab Savings Area (12,000 km^2), which together are 15% larger than the old Japanese no-trawl area, include less than half (48%) of the baseline broodstock. Ranked by the density (number per hour) of multiparous crab (Fig. 2), the Pot Sanctuary and the Japanese Broodstock Sanctuary were more effective at protecting the broodstock (and their preferred habitat) from trawling than today's refuges. The Pot Sanctuary protected not only the highest broodstock densities, but the multiparous females there were the largest females in Bristol Bay (Fig. 3). The relatively few multiparous females protected by today's Bristol Bay closure east of 162ºW longitude were the smallest. The distribution of the 1958 broodstock resulted in a northeast to southwest gradient of increasing reproductive value from the relatively barren grounds east of Port Moller to the essential habitat of the western end of the Alaska Peninsula and Unimak Island—habitat that used to be protected from trawling by the Pot Sanctuary. This 1958 gradient, hypothesized to be the consequence of an endless-belt reproductive strategy, persisted some 20 years later as a distinctive

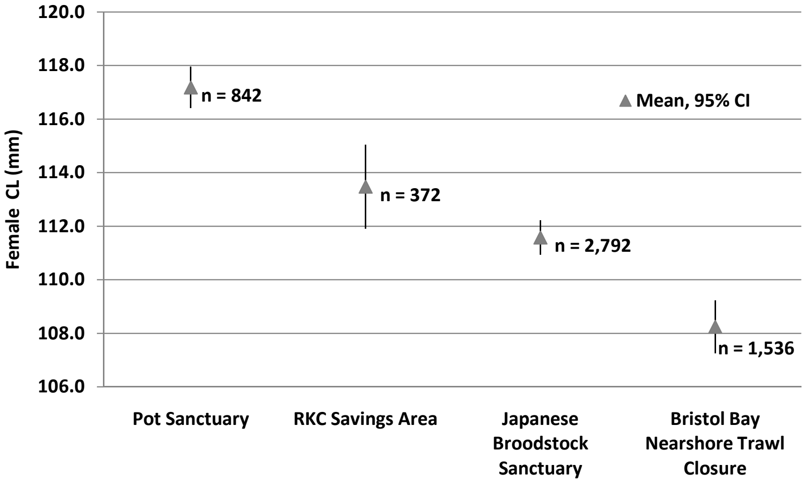

Figure 3. Size distribution among four no-trawl refuges of all measured female red king crabs collected from the baseline broodstock during late-phase sampling in June-July 1958 (NMFS unpubl. data). The largest females, i.e., those with the greatest reproductive value, were found in the Pot Sanctuary. The smallest females were found in today's Bristol Bay Nearshore Trawl Closure, east of 162°W latitude. n = number of crab.

feature of the 1975-1978 broodstock distribution, as pointed out by Dew and McConnaughey (2005).

The evidence suggests that the decision to abandon the relatively valuable Pot Sanctuary in favor of the Bristol Bay Nearshore Trawl Closure, an area largely uninhabited by the broodstock and only lightly plied by commercial trawlers, was based on considerations other than the preservation of the stock's reproductive potential. The stated purpose of the Bristol Bay closure was to protect juvenile red king crab and their habitat (Witherell and Woodby 2005), but this is a purpose inconsistent with the arithmetic of reproductive value (e.g., Fisher 1958, Slobodkin 1970, Wilson and Bossert 1971, Dew 1980). Moreover, survey data indicate that approximately half of the Bristol Bay closure comprises habitat of marginal value to, and only thinly populated by, juvenile and subadult king crab (Fig. 4). The relative sterility of a large proportion of the Bristol Bay closure was known as early as 1941 when a government survey reported that trawl catches along the Alaska Peninsula diminished moving from Port Moller eastward "until a drag off Ugashik (Fig. 4) resulted in a skunk haul" (USFWS 1942, p. 74).

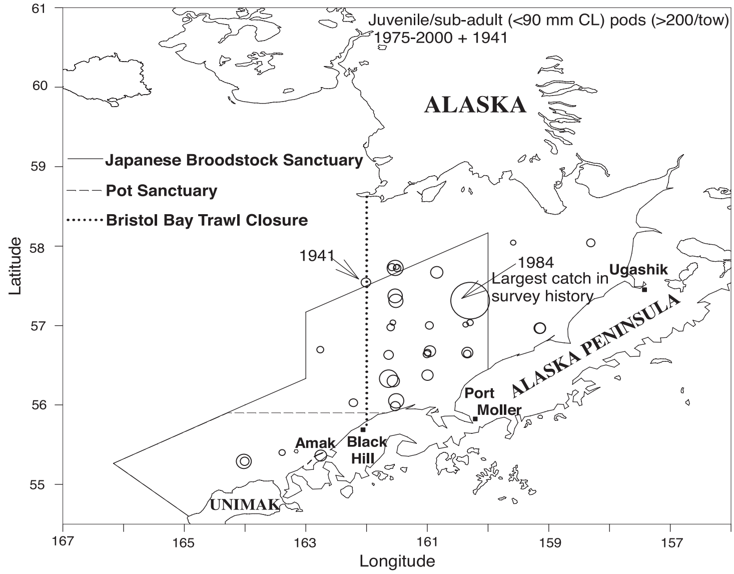

Figure 4. Location of juvenile pods of red king crab, 1975-2000, plus a single pod found in the 1941 survey (circle diameter indicates relative size of the aggregation). The Bristol Bay Nearshore Trawl Closure, designed specifically to protect juveniles and their habitat, included 87% of the podded juveniles; the Japanese Broodstock Sanctuary included 95%. Prime juvenile habitat does not extend east of 160°W.

Essential Fish Habitat Environmental Impact Statement misinformation

Once promulgated, an EIS is a legal document under NEPA (National Environmental Policy Act) and is used as a decision-making tool. Therefore, it is important to point out substantive error in the EFH EIS. There are several instances where the EFH EIS presents an inaccurate picture of the relative value of the historic no-trawl refuges and their respective roles in rebuilding a decimated red king crab stock. For example, the impression created by the following EFH EIS statement is incorrect and should be revised: “The area north of Unimak Island was very important habitat for red king crab females during the mid to late 1970s but was not particularly important prior to that time and has not been important since.” (NMFS 2005, p. L-17). This statement is inconsistent with existing knowledge, including the 1958 multiparous-female distribution, when 34% of the entire Bristol Bay broodstock (and perhaps half of the stock's reproductive value) was located in the waters off Unimak Island. Also, it is unlikely that negotiating governments, scientists, and fishermen would have located the Pot Sanctuary, a trawl-free refuge established specifically for red king crab, in waters that were not particularly important to the species. Once it is understood that a habitat was important to red king crab some fifty years ago in 1958, as well as during the mid to late 1970s (Dew and McConnaughey 2005), there is no reason to suspect that the habitat is not equally important to the stock's reproductive potential today, regardless of man's choice to transform the area from a sanctuary for Alaska's most productive broodstock to a trawling ground largely uninhabitable by king crab. Based on today's trawl-closure boundaries, habitat essential to more than half of the ancestral (1958) broodstock remains unprotected from trawling, which may explain why today's stock cannot rebuild to even half of its former abundance. However, according to a December 7, 2004, letter to the Alaska Marine Conservation Council, it is the opinion of NMFS scientists that ". . . evidence linking trawl closure areas to king crab recovery is scant." (NMFS 2004). Building on this opinion the EFH EIS (NMFS 2005, p. L-19) states: "The abundance of red king crabs in the late 1970s was anomalously high and should not be viewed as a realistic goal for restoring the population." However, it is illogical to imply that trawl closures are ineffectual and then to say that red king crab were anomalously successful at a time when 89% of the broodstock (versus today's 48%) was being protected by a well-designed 67,000 km^2 trawl closure. While evidence linking trawl closures to king crab recovery may be scant (due in part to poorly designed closure areas), there is ample, quantitative evidence linking trawling to severe population declines of 88-99% after the Japanese Broodstock Sanctuary and the Pot Sanctuary were opened to commercial trawling (Dew and McConnaughey 2005). It may be logically indefensible to maintain that the impact of trawling in red king crab habitat is negligible (NMFS 2005, p. B-34), and simultaneously to aver that today's relatively unprotected Bristol Bay red king crab cannot be restored to earlier, "anomalously high" levels of abundance that occurred during a regime of effective protection from trawling.

Two management philosophies

Nearly a half-century ago, managers and scientists concerned for the future of Alaska's premier seafood resource believed that the spatial distribution of Bering Sea red king crab, as mediated through the species' habitat preferences, was predictable to the extent that more than 20,000 km^2 of habitat essential to king crab could be set aside as a trawl-free refuge (the Pot Sanctuary) to protect the king crab resource. In contrast, much of today's scientific and management community apparently believes that red king crab are so unpredictable in their movements that it is impractical and perhaps incautious to designate essential habitat with any precision greater than that required to draw a line around a 150,000 km^2 area encompassing the species' approximate geographical range within the Bering Sea (NOAA 1999, NMFS 2005).

The watershed event separating these two management philosophies was the 1981 collapse of the Bristol Bay red king crab stock, an event so sudden, unexpected, and catastrophic that managers were left without a plausible explanation until the regime-shift theory expanded to fill the void. Basically, the regime-shift theory advances the premise that, contemporary with record levels of fishing mortality (Dew and McConnaughey 2005), warmer water temperatures after 1976-77 acted, directly or indirectly, to increase the natural mortality of adult crab, thereby effecting a precipitous (1980-83) decline of more than 90% in the standing stock of Bristol Bay red king crab. Since the king crab collapse, reliance on the idea that temperature is the dominant ecological factor governing the distribution and abundance of crabs has become almost total (e.g., Loher and Armstrong 2005, Yeung and McConnaughey 2006). For example, in the EFH EIS, NMFS dismissed concerns that that the report did not adequately consider the effect of trawling on the distribution and abundance of crab, stating that ". . . changes in crab distribution and abundance appear to be attributable to changes in water temperature." (NMFS 2005, p. L-17). However, the relationship among abundance, distribution, and temperature is not well understood, and there is little agreement as to the directionality of the hypothesized relationship. Regime-shift proponents claim that the crab died off because of water temperatures slightly (2-3°C) warmer (e.g., Yeung and McConnaughey 2006) than the long-term mean; others (e.g., Loher and Armstrong 2005) claim that Bristol Bay red king crab avoid temperatures slightly (2-3°C) colder than the long-term mean. Taken together, these hypotheses require a degree of stenothermy uncharacteristic of a boreal species with an exceptionally wide temperature tolerance (Matishov et al. 2008). The species molts and grows during a six-month, winter-spring period, reproduces from January through June, forages and incubates its eggs during all months of the year, and conducts these major life functions in waters ranging from very shallow to greater than 100 m, a depth range within which temperature at any given time varies by several degrees. Also, as noted by Loher and Armstrong (2005), avoidance of low temperatures by red king crab does not explain the sudden loss of tens of millions of adult crab from the warmer southwestern sector of their Bristol Bay habitat near Unimak and Amak islands. Nor is there credible evidence for an unusual spike in fish predation or disease, mechanisms through which the regime shift, with its associated but transitory increase in temperature, is proposed to have acted to increase the natural mortality of adult king crab to catastrophic levels (Dew and McConnaughey 2005). Ultimately there is no hypothesis that can account for the spatially explicit disappearance of very large numbers of adult crab without including the lethal effects of bottom trawling within habitat essential to red king crab.

If it were true that water temperature was the dominant factor in determining where red king crab were found in the southeastern Bering Sea, then it would be difficult to designate any specific geographic location as essential habitat, given that bottom temperatures at the same location can vary substantially, even between consecutive years. For example, in Bristol Bay water 50-60 m deep off Black Hill, bottom temperature was 2.5 to 3.0°C in May 1958 and –0.5 to 0.0°C in May 1959 (McLaughlin 1963). At the same location 40 years later, the bottom temperature was 5-6°C in June 1998 and 1-2°C in June 1999 (Loher and Armstrong 2005). The idea of crab being driven from one location to another by "thermal forcing" (e.g., Loher and Armstrong 2005) is inconsistent with information from years of fishing and research surveys indicating that, regardless of interannual temperature variations, red king crab over the past half century have tended to use the same spawning, incubation, molting, foraging, and overwintering grounds from one year to the next, unless physically prevented from doing so.

Habitat selection evolves because organisms in some habitats leave more descendants than organisms in other habitats (Krebs 1978). But some historical perspective is needed to identify habitat essential to an intact population of crab but no longer habitable because of human activities. This can be accomplished by using data and information from surveys conducted at a time when a relatively unexploited Bering Sea red king crab population was spatially distributed within its environment in a way that maximized its reproductive potential. The EFH EIS uses data from 1987-2002 to evaluate habitat essential to Bristol Bay red king crab (NMFS 2005). However, using information from pre-1981 (pre-collapse) surveys might improve upon the exercise of evaluating habitat importance based on the spatial distribution of a remnant population in the aftermath of a collapse that all but eliminated the species from areas where it was previously abundant. There is a "ratchet effect" associated with a decision-making process that tends to cede historically important crab habitat to the trawling industry. For example, commenting on the importance to red king crab of Bristol Bay habitat south of 56°N—habitat which trawlers value as rock sole trawling grounds—NMFS reported that "no female crab have been taken in this area during the 1990-1994 trawl surveys" (NOAA 1995, p. 4867). Omitted from consideration is the fact that this same area was once (1964-1977) the Pot Sanctuary, recognized by scientists and fishermen of three nations as essential red king crab habitat that was to be protected from trawling. Now that the former Pot Sanctuary is the most heavily trawled bottom community in the eastern Bering Sea, it is not surprising that the area is no longer habitable by broodstock aggregations.

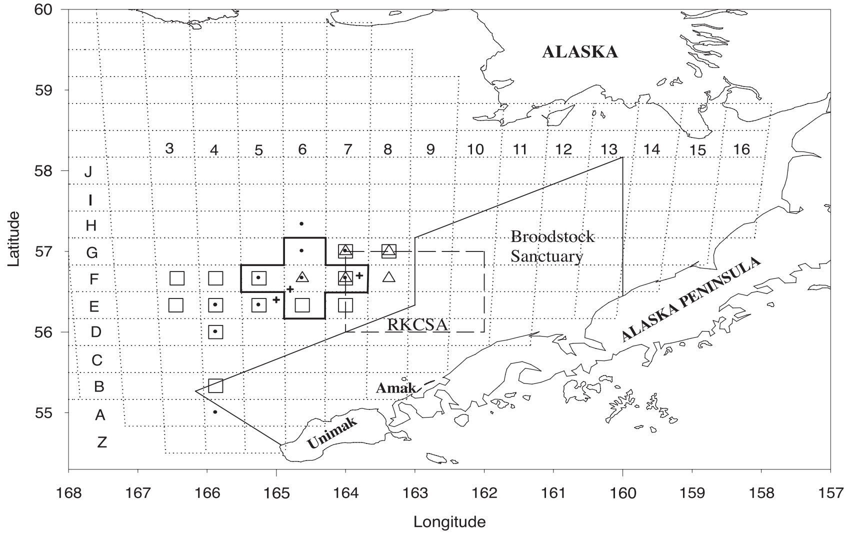

Figure 5. Location of male-only habitat in relation to the Japanese Broodstock Sanctuary and today's Red King Crab Savings Area (RKCSA). To qualify, a station must have produced ≥100 red king crab during the time period under consideration, ≥94% of which must be males. Time periods: 1958-1961 (□); 1975-1980 (•); 1984-1999 (Δ). The (+) symbols represent the northeast-shifting, crab-weighted center of distribution for each time period. Numbers of survey-caught male and female red king crab at five contiguous stations (outlined in bold) during 1975-2000 are in Table 2. Note that the Japanese Broodstock Sanctuary was designed to exclude the male-dominated habitat, which was the focal point of Japan's autumn tangle-net fishery (Takeshita et al. 1990).

Site fidelity

Site fidelity is an aspect of red king crab behavior that can be used to define essential habitat. When relatively dense concentrations of animals recur at a location year after year, irrespective of annual variations in water temperature, it is likely that some attribute of that particular habitat is essential. Because patterns of site fidelity can be disrupted or obliterated by fishing, it is important to search for such patterns using historical, pre-impact distribution and abundance data. A pattern of site fidelity notable for its stability over several decades is the recurrence of all-male molting aggregations west of the Japanese Broodstock Sanctuary (west of 163°W) and some 150-250 km north of Unimak Island. Using the criterion that 94 of 100 crab caught at a

Table 2. The cumulative sum of adult male (♂) and female (♀) red king crab and the proportion of males (p♂) collected during 1975-2000 within the male molting grounds west of 163°W. The 5,749 males collected at these five stations represent 21% of all mature males collected at the >100 Bristol Bay sampling stations during 1975-2000. This 26-year history indicates an overwhelming male dominance within this 6,860 km² area centered on station F6 (see Fig. 5).

	G6 ♂ = 237 ♀ = 1 p♂ = 1.00	
F5 ♂ = 501 ♀ = 4 p♂ = 0.99	F6 ♂ = 2,484 ♀ = 1 p♂ = 1.00	F7 ♂ = 1,402 ♀ = 26 p♂ = 0.98
	E6 ♂ = 1,125 ♀ = 142 p♂ = 0.89	

station must be male, survey data from 1958-1961 indicate that male habitat comprised 13 survey stations, generally within an 18,000 km² rectangle between 56-57°N and 163.5-166.5°W (Fig. 5). During 1975-1980 male habitat consisted of ten stations in a 14,000 km² rectangle between 56-57.3°N and 164-166°W. During the post-collapse years of 1984-1999, the habitat comprised five stations within a 7,000 km² area between 56.5-57°N and 163-165°W. During the period from 1958 to 2000 the male-only habitat area decreased by more than 60% and the center of distribution (**+** symbols, Fig. 5) moved some 80 km to the northeast, away from regions of relatively heavy trawling to the south and west (Dew and McConnaughey 2005).

Despite a substantial reduction in its areal extent and a systematic shift in its geographical center, each of which may be an effect of fishing, the spatial and temporal persistence of this site fidelity over a 40 to 50 year period is an important indicator of essential habitat. Also noteworthy is the very narrow and consistent demographic character of the phenomenon. Virtually all (>99%) of the 12,447 red king crab collected at the stations indicated in Fig. 5 were adult (≥120 mm CL), recently molted, new-shell males (102 were females). Notwithstanding assertions that the relative importance of habitats cannot be evaluated using stock-assessment surveys (e.g., DiCosimo 1999, NOAA 1999), a 26-year (1975-2000) history of survey catches at five contiguous Bristol Bay stations demonstrates the stability and predictability of male dominance within this approximately 7,000 km² area of red king crab habitat (Table 2, Fig. 5).

Because the annual surveys that encountered the all-male aggregations were conducted during the April to July spawning of multiparous females, and because the habitat where the all-male aggregations were located is more than 100 km from nearshore spawning grounds, it is likely that the crab in these aggregations did not participate in multiparous mating in the year they were captured, as noted by Dew (2008). This interpretation of the data is consistent with the results of previous investigators (Korolev 1964; Chebanov 1965; Rodin 1970, 1990; Takeshita et al. 1990). Moreover, in 1958 the U.S. Bureau of Commercial Fisheries reported that the distribution of large new-shell males was different from that of old-shell males. The distribution of old-shell males was similar to that of mature females, particularly during the spring mating period, leading investigators to conclude that only old-shell males were capable of mating (USBCF 1959). Today's managers do not acknowledge this aspect of red king crab ecology and believe that all males ≥120 mm CL, regardless of their molt status, mate with one or more females every year (Zheng et al. 1995).

Crab as habitat

Because ecology is the study of interactions that determine the distribution and abundance of organisms (Krebs 1978), EFH concepts should be anchored firmly in ecological principles. Instead, the EFH EIS (NMFS 2005, p. L-17) maintains that ". . . mortality from bycatch is unrelated to habitat concerns" and that "Habitat effects on crab concern effects on prey and on living and non-living structures on and in the ocean bottom. Effects on the population due to bycatch in trawl fisheries are not included as a habitat effect." (NMFS 2005, p. B-31). However, by severing the link between crab and their habitat, this EFH approach sets itself apart from the discipline of ecology, of which a central tenet is that a habitat is altered by the presence (or absence) of its inhabitants. That is, a habitat whose components include a population of red king crab will not be the same if the crab are significantly reduced or eliminated from the habitat. Attempts to evaluate the habitat effects of trawling while excluding from consideration the effects of trawling on a major component of the habitat (the crab themselves) is, from the perspective of an ecologist, intellectually untenable.

Consider that each successfully molted crab leaves behind a cast shell. These shells are composed of chitin, a polysaccharide polymer embedded in a hardened proteinaceous matrix that may itself comprise more than a hundred different proteins such as resilin, a glycine- and proline-rich protein that confers high elasticity to the cuticle of hinge regions (Anderson and Weis-Fogh 1964, Hojrup et al. 1986, Merzendorfer and Zimoch 2003). My own in situ observations indicate that molting in subadult and adult red king crab is a nocturnal mass phenomenon, where large aggregations of crab molt synchronously in a single night.

Figure 6. Cast shells of red king crab resulting from a single night's mass molt. There are no live crab in the photo. Environmental conditioning occurs as the molted casts decay and become part of the sediment. (Photo by B. Dew at Kodiak, Alaska).

The location of a mass molt is marked by a layer of cast shells lying on the bottom (Fig. 6), ready to be broken down into their biochemical constituents by bacteria, largely of the genus *Vibrio* (Bassler et al. 1991, Yu et al. 1991). The annual decomposition of hundreds of tons of chitin and protein on molting grounds is likely to alter the composition of local sediments in a way that serves as a biochemical marker for crab returning to the habitat. In this way, habitats that optimize molting success, and any life functions associated with it, would be the most heavily marked, thus perpetuating site fidelity such as that observed on male molting grounds north of Unimak Island. Optimum spawning grounds would be similarly marked, given that mating female red king crab are obligate molters. Therefore, by virtue of the molting process, crab are an inextricable part of the habitat in which they are most successful; and the loss of crab as trawl bycatch is a habitat issue, not simply a bycatch issue as asserted in the EFH EIS (NMFS 2005).

Depensation

Like red king crab, some organisms, when present in sufficient numbers, are able to modify their environment in ways that increase survival or reproductive success (Liermann and Hilborn 2001). For example, much has been written about how the carcasses of spawned-out salmon provide marine-derived nutrients to spawning streams, thus increasing juvenile survival (e.g., Larkin and Slaney 1997, Cederholm et al. 1999) and perhaps aiding in homing and natal stream recognition. Less familiar is the concept that environmental conditioning is evidence of depensation in a population (Liermann and Hilborn 2001) because whatever advantages the mechanism confers to the population become less effective at low abundance levels. In a population where depensation is operative, reproductive success (recruits per unit of spawner biomass) is lowest when the abundance of the spawning stock is lowest. By contrast, in a population regulated largely by compensatory mechanisms, reproductive success is highest when spawning-stock abundance is lowest. Compensation is at the core of the models used to manage Bering Sea crab stocks and is the basis for the assumption that calling a halt to fishing will permit an overfished stock to recover from extremely low abundance levels. Depensatory models require a minimum viable stock size if the population is to grow or even to survive at all. Management models such as the Ricker and Beverton-Holt models, which exclude the possibility of depensation in populations where it may exist (Liermann and Hilborn 2001), are likely to fail when the population falls below its critical level.

Relatively strong depensation should be expected in populations of highly social species that assemble and conduct their life functions in large, dense aggregations (Wilson 1975, p. 83) and act together to condition their environment, as do red king crab. Also, depensation should be suspected when overexploited populations fail to recover after fishing mortality is reduced or eliminated. In 1966, the Gulf of Alaska (GOA) provided the bulk of the U.S. red king crab catch (70,000 t vs. 450 t from the Bering Sea). However, after a period of overfishing during which the estimated GOA harvest rate rose to about 70% of the legal male stock (Orensanz et al. 1998), the fishery collapsed and was closed in 1983. Although there has been no GOA commercial fishery since 1982, there is no sign of a GOA stock recovery, even after 27 years. A similar situation exists for the Bristol Bay population, stuck at less than 20% of its 1975-1980 abundance for the past 28 years since its abrupt 1981 collapse. For populations with strong depensation, the success of rebuilding plans that rely on reducing or eliminating fishing mortality to increase stock size may be increasingly thwarted as the population's minimum stock-size threshold is approached and may be completely nullified when the stock is driven below this threshold. Jennings et al. (2001, p. 84) provide the following warning: "If depensation exists, fishery managers should be extremely nervous because fished stocks may not recover after being fished to very low abundance, even when fishing is stopped."

Summary

The sudden, unexpected collapse of Alaska's Bristol Bay red king crab population in the early 1980s, after years of record harvests, came as a shock to those responsible for the well-being of the resource. Managers quickly decided that the collapse was due to natural causes related to climate change (regime shift) and unrelated to fishing (Otto 1986). However, as pointed out by Dew and McConnaughey (2005), it is difficult to make the case for natural causes without first accounting for the effects of fishing. But such accounting cannot be accomplished if underlying assumptions are invalid. For example, it is not likely that managers, modelers, and scientists would be able to differentiate between the effects of fishing and climate change without understanding that, based on available evidence, male red king crab do not molt and mate in the same year. Also, it may be difficult to invoke climate change as a primary cause of the decline and long refractory phase of a stock that has lost more than half of its reproductive potential over the past 30 years through the loss of essential habitat deemed by managers to be of no particular importance to the stock (NMFS 2005).

The EFH EIS (NMFS 2005) rationale that red king crab are unpredictably shunted about by regime shifts and temperature changes understates the role of fishing, especially bottom trawling, in shaping the spatial distributions observed today. It is possible that a species' contemporary distribution may reflect only those individuals that remain after fishing has rendered the prime grounds uninhabitable. The contemporary distribution may in fact consist only of marginal habitat rather than the habitat that was important to the ancestral stock. The EFH EIS uses no data earlier than 1987 to make its conclusions on habitat essential to red king crab. But by 1987, prime king crab habitat off the western end of the Alaska Peninsula had already been ceded to the bottom-fish industry and had become the most heavily trawled area in the eastern Bering Sea. Formerly this area was a red king crab no-trawl refuge known as the Pot Sanctuary, recognized by the scientists of three nations as habitat essential to the crab. But now the area is depauperate of crab and known as Cod Alley, and the EFH EIS declares that the area was not and is not important to red king crab.

According to those like Lowell Wakefield who risked their fortunes and lives in the pursuit of red king crab, the species' habitat preference and predictability were remarkable and obvious, as were the effects of trawling on red king crab aggregations (Blackford 1979). The crab could frequently be found at certain spots at particular times. Taking advantage of the podding and homing behavior of the crab, Wakefield's trawling crew devised "radar fishing" to help them stay on the foraging crab aggregations so they could work over an area and clean out an entire school. Some early observations from Wakefield's trawling operations, as inferred from Blackford (1979), should be of interest to today's managers: (a) the preferred habitat of red king crab was centered around Amak Island in the late 1940s and 1950s, and was predictable in time and space; (b) the behavior of red king crab, including podding and site fidelity, increases the species' vulnerability to trawling; (c) red king crab aggregations and local subpopulations can be wiped out by trawling; (d) after a red king crab fishery begins, the crab are first eliminated from habitats where they're most abundant; and (e) the longer the commercial-fishing history, the less useful is today's distribution in defining habitat essential to the crab. To a remarkable extent, the information and conclusions in the EFH EIS (NMFS 2005), a document that presumably reflects the best thinking of those responsible for the well-being of Alaska's red king crab stocks, are inconsistent with first-hand experiences and field observations recorded over the past 70 years.

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